FINAL TECHNICAL REPORT

Economical Recovery of Fly Ash-Derived Magnetics and Evaluation for Coal Cleaning
(KEOP Solicitation Number 06-KEOP-01)

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Project Description

The project goal is to demonstrate that high density, magnetic material can be economically recovered from coal combustion ash and be effectively utilized to address the shortage of magnetite used as heavy media for efficient coal cleaning. Approximately half of the coal preparation plants in Kentucky utilize heavy media processing to remove impurities from mined coal in order to significantly increase the heating value of the coal, reduce transportation costs and lower the amount of ash and SO_2 that must be removed from emission streams by the utilities that utilize the coal. The coal industry in Kentucky utilizes approximately 130,000 tons of magnetite annually. During the past two years, China's increased demand for magnetite has generated concerns about the long term availability and cost. Over the last 6 months, the delivered cost of magnetite for Kentucky operators has increased 2.5 times since 2001. A supply shortage in the future would have a significant impact on the ability to supply clean coal to Kentucky utilities.

The goal of the project is to demonstrate that magnetic material can be economically recovered from combustion ash at a suitable grade for use as heavy media. While this concept has been attempted at the commercial scale numerous times in the past, each attempt was unsuccessful, not for technical reasons, but for economic reasons. There is simply an insufficient amount of magnetic material present in fly ash to economically justify recovering this material as a single product.

For this reason, this project focused on incorporating magnetite recovery into a process flowsheet that recovered additional products from combustion ash. One such flowsheet was developed at the University of Kentucky Center for Applied Energy Research (CAER) and is referred to as the *FastFloat* process. The concept of the *FastFloat* process is to utilize physical beneficiation to recover a variety of marketable products from combustion ash, including construction aggregate and fill sand, carbon fuel, pozzolan for cement replacement, cenospheres and mineral-grade filler. While a recovery process may not be economically feasible for each of these products individually, a process that recovers several of these products simultaneously has been shown to be economically justified. The overall goal of this project was to first show that magnetite recovery could be economically incorporated into the *FastFloat* or similar ash beneficiation flowsheet, and second, to demonstrate that the recovered magnetite product could be used as a substitute for mineral magnetite in dense medium separation.

Project Site Selection

In order to improve the processing economics for recovering magnetite from combustion ash, it was first necessary to select a substrate that contained a sufficient amount of the magnetic material. Preliminary site selection was limited to Kentucky utilities that burned high sulfur coal since it has been well established that the high iron content of these coals leads to the production of larger amounts of magnetite.

The second criteria was to select a site that was either practicing ash beneficiation to recover marketable products in some form or planned on doing so in the future. Based on these criteria, three candidate utility sites were selected, Ghent Station, Mill Creek and Trimble County. All three of these utilities currently burn high sulfur coal and incorporate flue gas scrubbing to limit SO_2 emissions. A bottom ash processing plant is currently in operation at Mill Creek. This facility produces 80,000 tpy construction grade fill sand from bottom ash and discharges -100 mesh fines as a reject stream. Ghent

Station and Mill Creek are candidate sites for ash beneficiation to produce pozzolan or filler from fly ash using the *FastFloat* or similar process. In this approach, a reject stream enriched in magnetite is generated from the primary classification processing stage.

Samples of the Mill Creek fill sand -100 mesh reject stream were obtained from the site for evaluation. Since no beneficiation is currently in practice at either Ghent Station or Trimble County, samples of fly ash were obtained from these sites and processed at CAER to simulate the appropriate ash beneficiation process. The results of this preliminary evaluation are summarized in Table 1.

Table 1. Summary of Candidate Test Sites.					
Power Plant	Size MW	Location	Principle Ash Beneficiation Product	Process Reject Stream	Magnetite Yield Wt %
Ghent	2226	Ghent, KY	Pozzolan	Primary Classification	2.7
Mill Creek	1717	Louisville, KY	Fill Sand	Screen Effluent	12.1
Trimble Co.	566	Bedford, KY	Filler	Primary Classification	5.3

Based upon this preliminary evaluation, Mill Creek was selected as the test site. Not only was the magnetite yield from this site significantly higher than from the other candidate sites, a commercial-scale ash beneficiation process is currently in operation. Pending successful results, incorporating magnetite recovery into the current flowsheet would improve the overall economic viability.

Site Description

Bottom ash is currently processed at Mill Creek by Charah, Inc,, an ash management company based in Louisville, KY. The process was jointly developed by Charah, Inc and CAER and has been in commercial operation since 2002 and has successfully marketed over 500,000 tons of graded fill sand produced from the bottom ash at Mill Creek.

Bottom ash is sluiced from the boilers into a trench that flows into the ash pond. The trench is periodically excavated with a track hoe and excavated material is stockpiled and allowed to drain. Material removed from the trench closest to the sluice entry point contains pyrite and is thus not suitable for beneficial reuse. The other excavated material is transported to a feed hopper by front end loaders and conveyed into a processing plant where oversize (+3/8 inch) material is rejected. The -3/8 inch ash drops into sump containing a screw classifier, which dewaters the ash and conveys the finished fill sand onto a stockpile. The sump overflow is a dilute slurry containing primarily -100 mesh (-150 μm) solids, which flow into a separate reject containment area, which is periodically excavated, again with a track hoe, and the fine solids are allowed to drain. The stockpiled fines are currently utilized as kiln feed by a nearby cement manufacturing plant, namely Cemex's Cosmos plant. This stockpiled fines reject was the substrate used for magnetite recovery.

Task 1. Magnetite Recovery

A flowsheet of the magnetite recovery circuit used is shown in Figure 1. The equipment was assembled on a 26 ft trailer and transported to the test site. A diesel generator was also hauled to the site to provide required electrical service along with a 2000 gallon portable water tank which was periodically filled for process water.
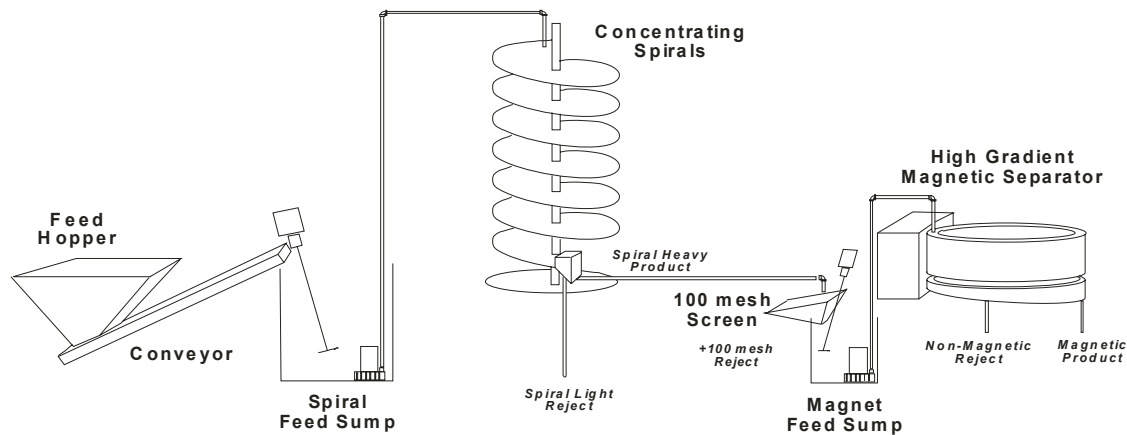

Figure 1. Magnetite recovery process flowsheet.

Stockpiled fines were excavated with a Bobcat loader, dumped into a feed hopper and conveyed into an agitated mix tank, where sufficient water was added to maintain a pulp density of 10% solids by weight. The slurry was fed onto a single bank of concentrating spirals with a feed pump. A multiple valve arrangement allowed for the feed rate to the spirals to be maintained at 35 gpm. As the slurry flowed down the spirals, the dense magnetite concentrated on the innermost section of the race, while lighter (i.e. less dense) fine ash and most of the water reported to the outermost section of the race. At the base of the spirals, splitters diverted the water and lighter ash back into the ash pond as a reject stream while dense magnetite was recovered from the inside race where it was collected.

Task 2. Magnetite Up-Grading

Material coarser than +100 mesh was removed with a vibrating screen and the -100 mesh magnetite was then fed into a continuous High Gradient Magnetic Separator (HGMS) to further upgrade the magnetite by removing entrained non-magnetic material. Figure 1 shows a continuous process; however, magnetic separation was actually conducted at CAER. This decision was made primarily out of safety concerns since the HGMS was not weather-proof and hence, not suitable for outside use.

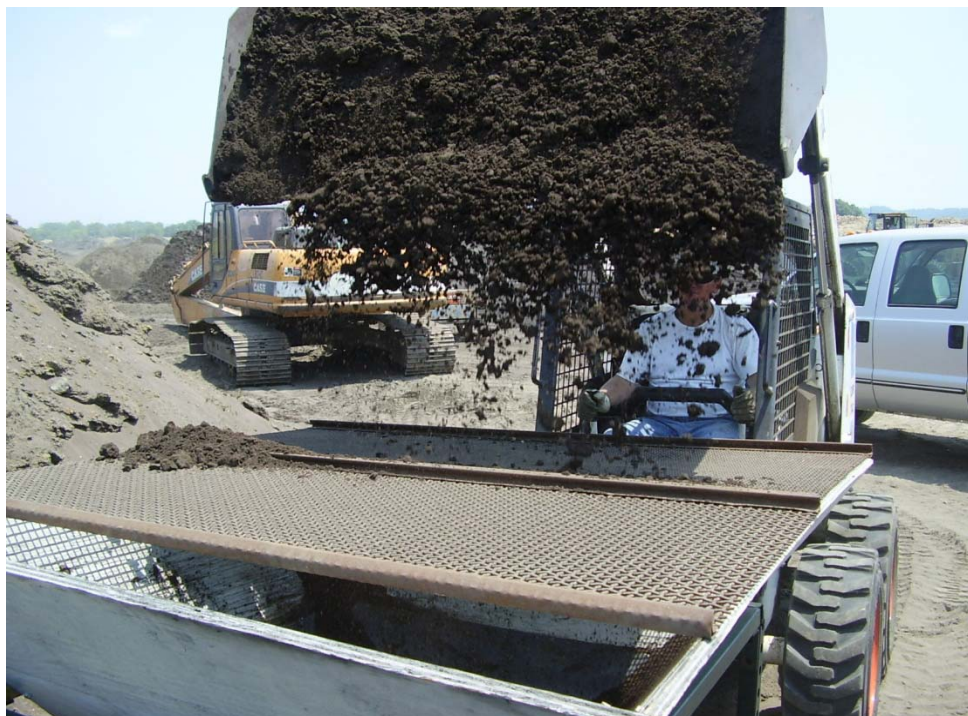Figure 2. Feed Hopper, Conveyor, Feed Tank, Spirals and Generator.

Figure 3. Bobcat loading ash into feed hopper.

Figure 4. Spiral Feed Tank.

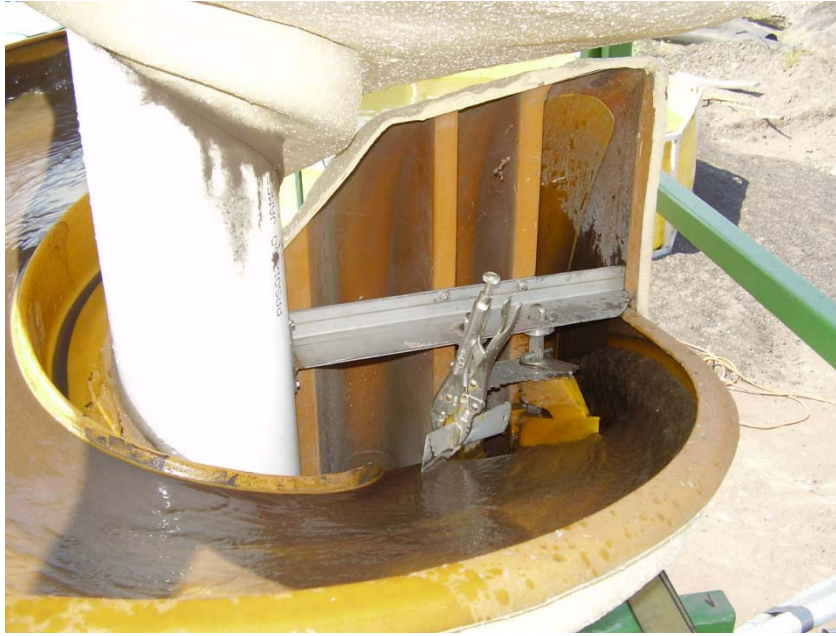Figure 5. Concentrating Spirals.

Figure 6. Splitter arrangement at base of spirals.

Figure 7. 2000 gallon process water tank. Fill sand
product stockpile in background.

A summary of results obtained during magnetite recovery activities at Mill Creek are presented in Figure 8. These results were compiled by obtaining periodic samples during processing, evaluating results and compiling incremental results. All samples were dried to record weights and a representative 50 gram aliquot was retained to determine the magnetic content by Davis Tube magnetic separation (DTMS). The weight
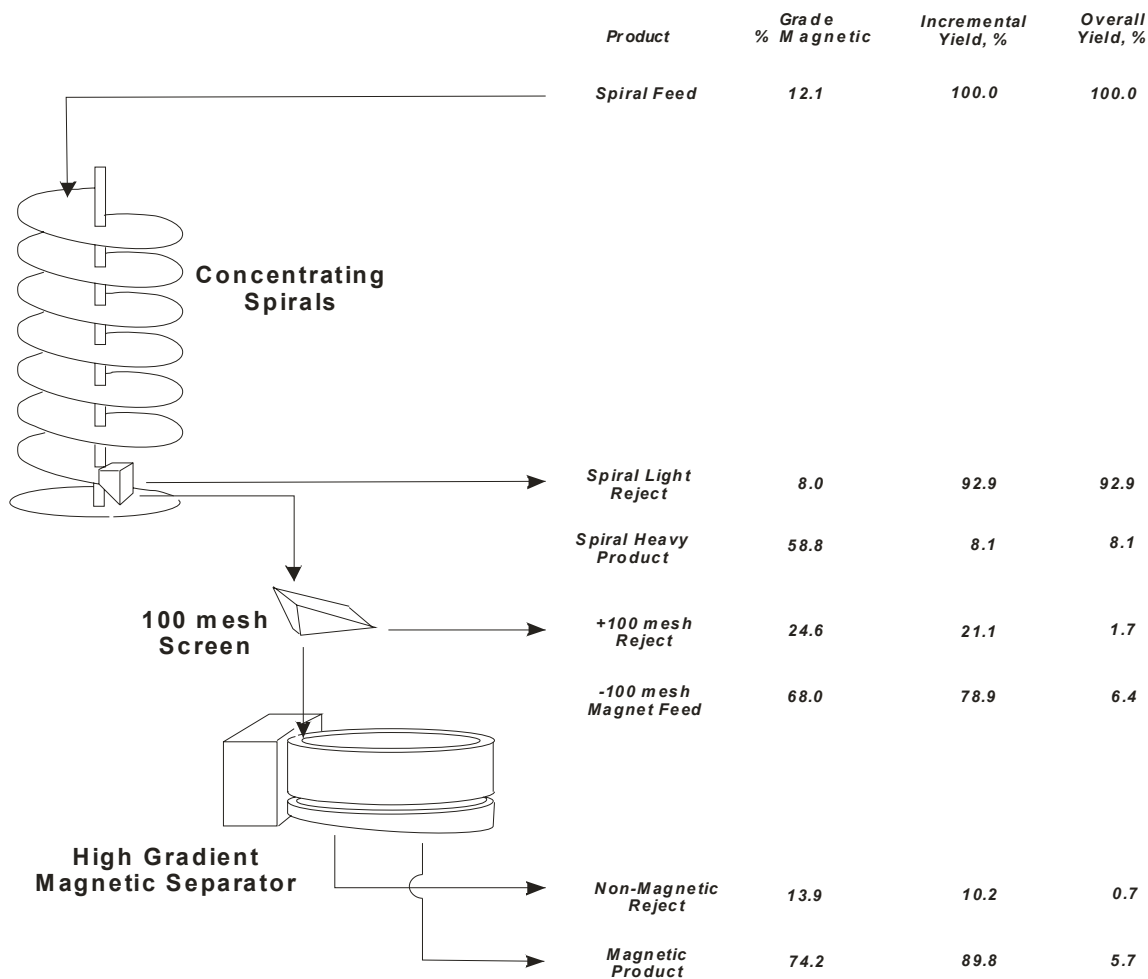
Product	Grade % Magnetic	Incremental Yield, %	Overall Yield, %
Spiral Feed	12.1	100.0	100.0
Spiral Light Reject	8.0	92.9	92.9
Spiral Heavy Product	58.8	8.1	8.1
+100 mesh Reject	24.6	21.1	1.7
-100 mesh Magnet Feed	68.0	78.9	6.4
Non-Magnetic Reject	13.9	10.2	0.7
Magnetic Product	74.2	89.8	5.7

Concentrating Spirals

100 mesh Screen

High Gradient Magnetic Separator

Figure 8. Summary of magnetite recovery results.

of any material retained in the magnetic field of the Davis Tube after two passes was defined as magnetic. The results shown in Figure 8 summarize the grade of each product stream, the incremental yield of each individual separation process, and the overall yield, as a weight % of the feed to the spirals.

The feed ash (12.1% magnetics) was up-graded to 58.8% magnetics by spiral concentration and the spiral reject contained 8% magnetics. The overall yield of the spiral concentrating process was 8.1%. The spiral product was then screened to remove +100 mesh material, which contained 24.6% magnetics. The screening step removed 21.1% of the screen feed (1.7% of the overall feed) and the resulting -100 mesh material was further up-graded to 68.0% magnetics. At this point in the process, the overall yield was 6.4%. The final processing step was magnetic separation, which rejected 10.2% of the magnet feed (13.9% magnetics) and provided a product containing 74.2% magnetics.

The overall process yield of the final product was 5.7% or 114 lbs of magnetite per ton of process feed.

Task 3: Magnetite Characterization

Representative samples of the +100 mesh spiral product and HGMS products were submitted for analysis by X Ray Fluorescence (XRF) and the results are summarized in Table 2. These results show that the final product contained 59.58% Fe_2O_3 with SiO_2 and Al_2O_3 as the major contaminants. HGMS non-magnetic reject and -50+100 mesh spiral oversize contained lesser amounts of Fe_2O_3 with higher proportions of SiO_2 and Al_2O_3.

Table 2. XRF Analyses of HGMS Products and -50_100mesh Spiral Product.			
	HGMS Magnetic Product	HGMS Non-magnetic Product	-50+100 mesh Spiral Product
SiO_2, %	26.07	49.04	42.16
Al_2O_3, %	8.38	12.27	14.32
Fe_2O_3, %	59.58	22.6	31.14
CaO, %	3.18	6.44	6.46
MgO, %	0.41	0.85	0.76
Na_2O, %	0.32	0.51	0.44
K_2O, %	1.07	1.72	1.87
P_2O_5, %	0.31	1.21	0.63
TiO_2, %	0.6	0.79	0.80
SO_3, %	0.89	3.14	1.14

Petrographic analyses showed that the final product was comprised essentially of spherical Fe-rich particles, some of which were fused with Si and Al. The non-magnetic particles were also spherical, but contained Si and Al-enriched spheres fused with lesser amounts of Fe (Figures 9 through 12).
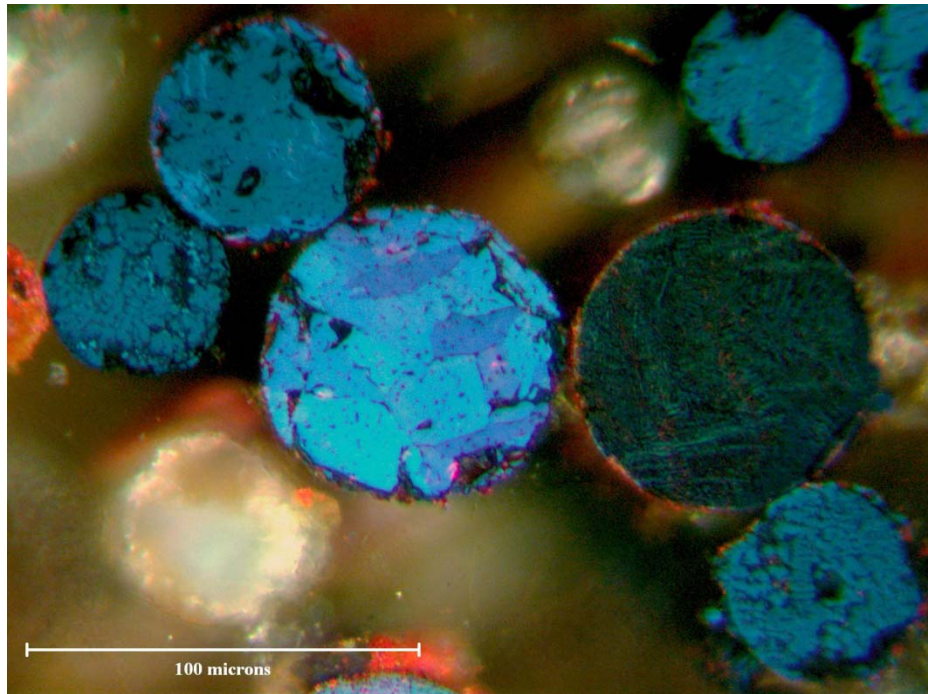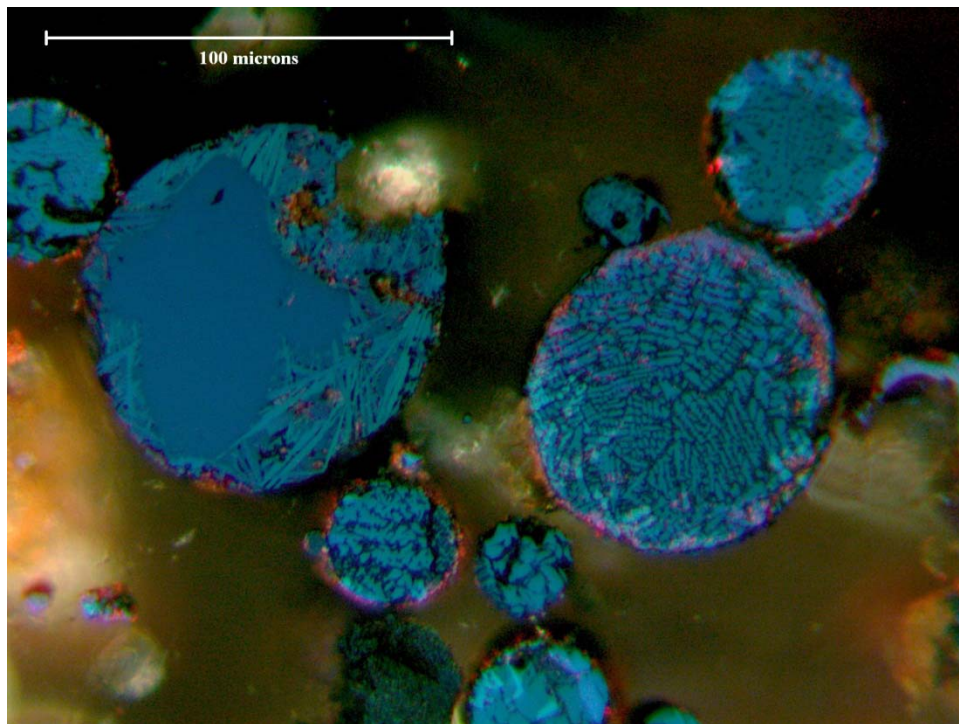
Figure 9. Spinel spheres in HGMS product.

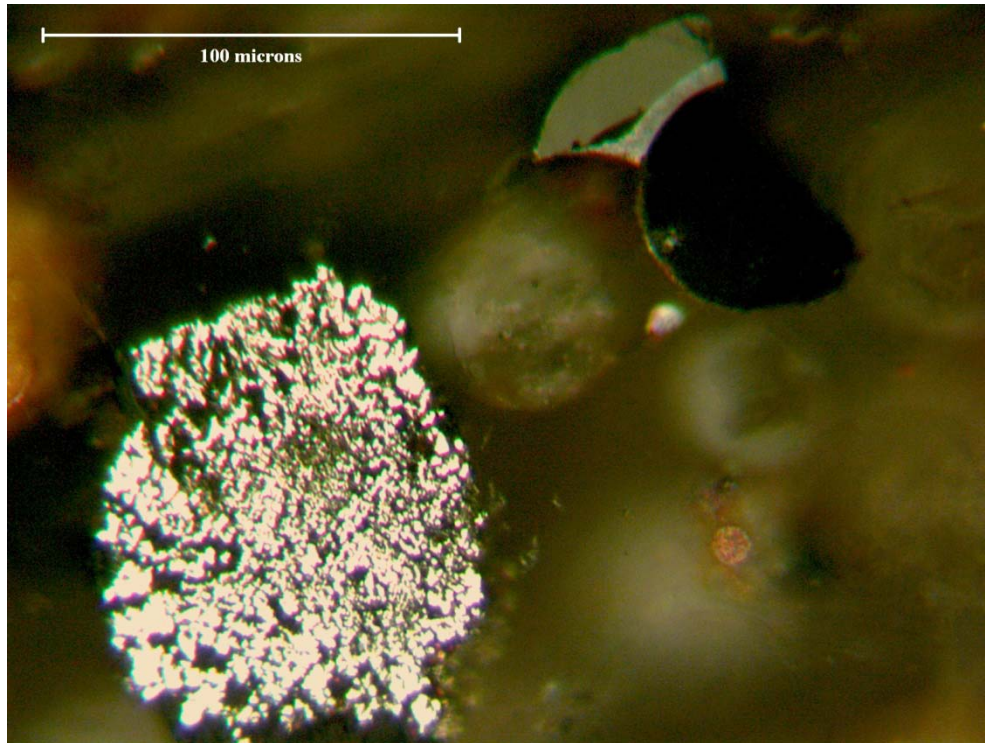Figure 10. Spinel spheres in HGMS product.

Figure 11. Spinel with glass (upper right); sulfide (lower left) in HGMS non-magnetics
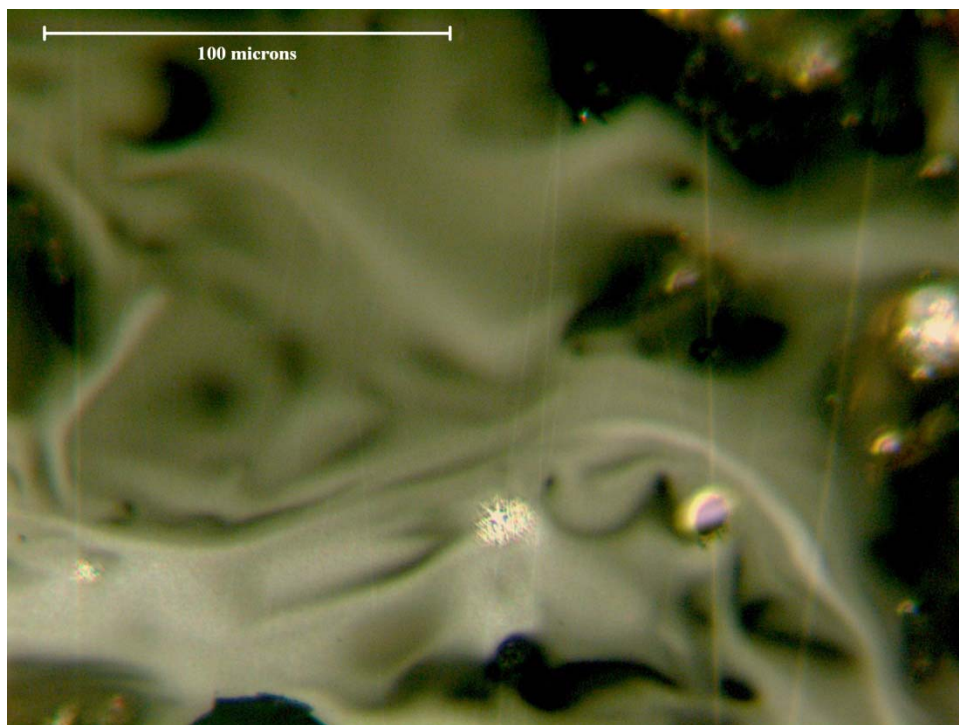

Figure 12. Glass with fine spinel inclusions in HGMS non-magnetics.

Task 4: Coal Sample Collection and Characterization

The coal sample used for the performance assessment of the medium was obtained from the dense medium cyclone process streams of an operating coal preparation plant that treats coal extracted from the Coalburg seam. The coal seam is prominent throughout the central Appalachia coalfields including eastern Kentucky and is well known as being difficult-to-clean due to the relatively large amount of middling particles present in the coal. Samples of product and reject streams from the heavy media cyclone circuit were collected into 208 liter (55 gallon) drums. The clean coal and reject coal were dry screened using 6 mm (1/4 inch) and 0.6 mm (28 mesh) screens and the size fraction 6 × 0.6 mm was retained. The oversize particles were crushed using a laboratory hammer mill and the product was rescreened to obtain the 6 × 0.6 mm size fraction and combined with the previously obtained material. The samples of clean coal and reject coal were blended completely and the blend was used as feed for the dense medium cyclone performance tests.

Representative samples were wet screened and each size fraction weighed and assayed for ash content. The results of ash analysis shown in Table 3 indicate that majority of the mass existed in the 3.4 × 0.9 mm fraction of the coal sample. The total ash content of the sample was 31.04, which was well distributed in each size fraction.

Table 3. Particle size-by-size weight distribution and ash content for the 6 × 0.6 mm Coalburg coal sample.		
Particle Size (mm)	Weight (%)	Ash (%)
+4.8	8.26	35.99
4.8 x 3.4	5.50	37.09
3.4 x 2.4	15.60	30.67
2.4 x 1.4	23.85	28.44
1.4 x 1.0	19.27	27.55
1.0 x 0.9	15.60	31.57
0.9 x 0.6	7.34	35.01
-0.6	4.59	36.18
Total	100.00	31.04

The Coalburg coal seam is known for its moderately difficult cleaning characteristics. This is due to the presence of high amounts of near gravity material. Based on the washability data in Table 4, the coal can be classified difficult-to-clean as indicated by a cleaning index (C.I = 1.3 cumulative weight % float / 1.6 cumulative weight % float) of 0.55 and over 20% of the feed mass within ±0.1 relative density units over a wide density range, i.e., 1.4 and 1.9 RD.

| Table 4. Washability data of the Coalburg coal.		
Specific Gravity	Weight %	Ash %
1.3 float	27.87	2.88
1.30 x 1.40	11.63	9.03
1.40 x 1.50	5.78	18.41
1.50 x 1.60	5.60	28.90
1.60x 1.75	11.95	39.66
1.75 x 1.90	16.40	48.78
1.90 x 2.0	9.50	59.41
2.0 sink	11.27	79.07
Total	100.00	31.83

Task 5: Dense-Medium Cyclone Tests

Pilot-Scale Dense Medium Cyclone Test Program

The tests utilizing the recovered magnetic product as a medium for cleaning coal were conducted using a 15-cm (6-inch) diameter Krebs dense medium cyclone with a 6.3 cm vortex and 4.5 cm apex diameter. The cyclone had a cone angle of 20° and was inclined at an angle of 10° from the horizontal. These parameters were kept constant throughout the entire study.

The dense medium cyclone was set to operate in closed loop. Figure 13 shows the closed loop circuit set up of the dense medium cyclone. The feed to the cyclone is pumped from the feed sump with the overflow and underflow streams reporting back to the sump. A feed bypass also reported to the sump, which was used to collect samples of feed to cyclone. The feed pump was used to control the inlet feed pressure to the cyclone between 17 and 69 kPa (2.5 and 10 psi).

The evaluation of the material was conducted in two phases. The objective of the first phase was to evaluate the stability of the medium. The second phase evaluated the performances achieved using the medium when treating 6 × 0.6 mm Coalburg coal, which has relatively difficult cleaning characteristics.
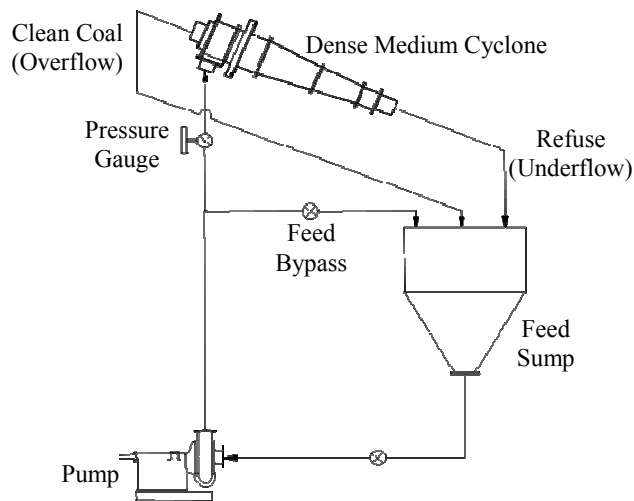
Figure 13. Schematic diagram of the dense medium cyclone circuit.

At the beginning of each stability test, the relative density of medium, which is a suspension of water and the high density magnetic material, was adjusted to the desired value in the circuit feed sump. The density was measured using a Marcy density scale. The medium was pumped to the cyclone at a pre-selected feed inlet pressure. A time interval of 10 minutes was allowed for the medium to stabilize. Samples were taken from the underflow and overflow streams to calculate the density differential between the two streams. The stability of the material was tested over a range of relative medium density values from 1.3 to 1.7 RD.

In the second phase of the experimental program, the medium was adjusted to the desired value and then the coal sample was added to the medium with the amount equivalent to achieve a medium-to-coal ratio of about 4:1. Again, a time interval of 10 minutes was allowed to ensure adequate mixing and steady state conditions. Samples from the overflow (clean coal and medium) and underflow (reject and medium) streams were taken simultaneously. Also, a feed sample was obtained from the bypass feed stream. The samples collected were wet screened using a 419 µm (40 mesh) screen to separate the medium from the coal. Each coal sample was split into two factions for washability analysis and ash content. These results were used for data analysis and performance assessment of the medium.

Medium Stabilization

One of the most important characteristics of a medium using for density-based separations is that the ultrafine particles used to develop the medium move nearly or completely with the fluid. In other words, the particles should not have a significant settling rate within the fluid. Generally, particle settling rate is a function of the particle size, shape and density as well as the particle population and medium viscosity. The relative density (RD) of the magnetic bottom ash particles was determined to be 3.44RD.

A sufficiently high particle population is generally required to induce hindered settling conditions. However, excessively high particle concentrations lead to a viscous medium which negatively impacts the density-based separation performance. Medium stability is assessed in a dense medium cyclone by measuring the difference in the pulp density values between the overflow and underflow stream densities (i.e., ρ_u - ρ_o). The general criterion for ensuring optimum performance is that the pulp density difference should be less than 0.4 units.

The bottom ash product obtained from the High Gradient Magnetic Separator was evaluated to assess the medium stability provided by the suspension over a range of medium density values typically used in cleaning coal. The medium formed by the suspension of the magnetic bottom ash was unstable with density differential values being over 0.8 density units as shown in Figure 14. The spherical shape of the bottom ash particles and their relatively large size were identified as the characteristics yielding an unstable suspension.
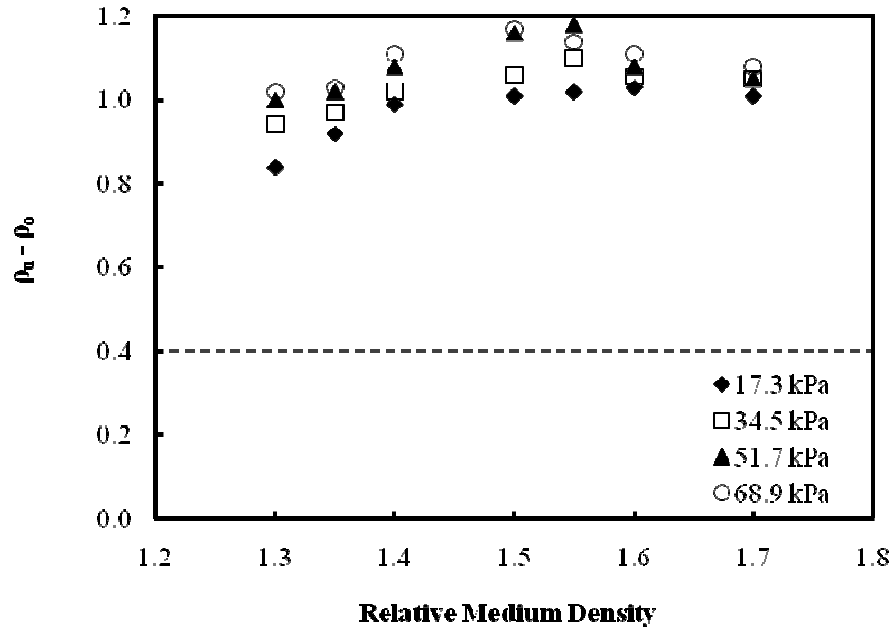

Figure 14. Medium stability achieved using the unground magnetic bottom ash material over a range of inlet pressures and medium.

In an effort to achieve a stable medium from the magnetic bottom ash material, the material was ground in a ball mill. To identify the appropriate amount of grinding, an initial study was performed in a laboratory Union Process attrition mill in which grinding time was varied. Medium stabilization was assessed qualitatively by observing the settling of particles within the suspension in a 2-liter glass cylinder. The attritor was a stirred ball mill with a capacity of 9.5 liters capable of batch operation. The grinding medium consisted of 0.64 cm (1/4-inch) diameter tungsten carbide balls. The attritor had a variable speed drive and which permited operational speeds of 65 to 500 rpm.

The magnetic bottom ash was mixed with water to make slurry of volumetric concentration 30% solid and was fed to the mill. A speed of 250 rpm was chosen for the tests so as to maintain a constant rotational velocity throughout the test. To vary the grinding time in the attritor, samples were collected at every 5 minute interval. The collected samples were dried and particle size analysis was carried out. The results from the analysis are summarized in Table 5.

| Table 5. Effect of grinding time in the attritor on particle size distribution.							
Particle Size, μm	Grinding Time, minutes						
	0	5	10	15	20	25	30
+150	4.59	0	0	0	0	0	0
150 x 74	50.16	12.33	0	0	0	0	0
74 x 44	32.71	35.90	14.08	3.08	0.75	0.04	0
44 x 37	5.61	12.52	14.29	6.68	2.67	0.90	0
37 x 25	5.07	17.95	23.59	23.82	16.75	11.32	6.20
-25	1.86	21.30	48.04	66.32	79.84	87.74	93.80

The results indicated that the particle size distribution shifted towards the finer size fractions with an increase grind time. The particle size distributions of the various grind products were compared with conventional magnetite. These comparisons led to the preliminary idea that the grind time on the HGMS product needed to be varied between 5 min to 10 minutes to achieve a material that has characteristics nearly similar to that of conventional magnetite.

The samples collected from the attritor were analyzed under a scanning electron microscope to investigate the effect of grinding on particle shape. As indicated in Figure 15, grinding decreased the sphericity of the particles and generated irregularly shaped particles. The loss of sphericity of the particles is desired for a stable medium due to elevated turbulent drag forces on the suspended particles which decreases the settling rate of the particles making up the medium.
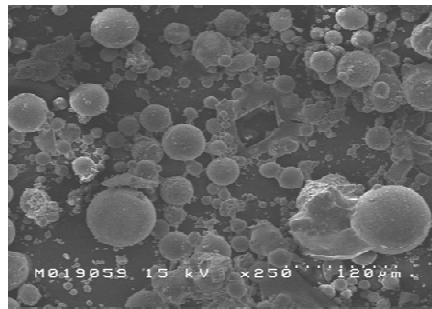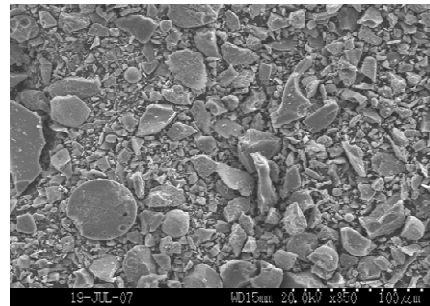
Original
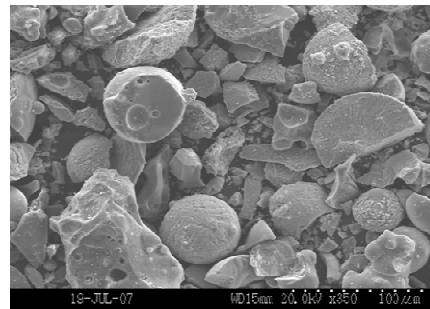
5 min grind
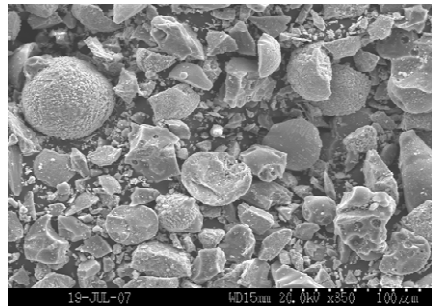
10 min grind

15 min grind

Figure 15. Scanning electron microscope images showing the particle size and shape changes.

To obtain a sufficient amount of material for the dense medium cyclone test program, the magnetic bottom ash material was ground in a pilot-scale ball mill circuit in continuous mode as shown in the Figure 16. The material was dry fed using a belt feeder and mixed with calculated amounts of water to maintain the pulp density at 33% solids by weight. The active grind volume in the ball mill was calculated to be 12% of the total volume. The retention time of material in the ball mill was controlled by controlling the feed rate. A representative sample was collected to analyze the change in the particle size distribution as a result of grinding.

Retention time in the ball mill was defined as the time taken by a particle to travel across the ball mill from feed end to the product end. The ball mill circuit set up was operated in open circuit with no recycle. The retention time was directly controlled by the feed rate to the ball mill. Lower feed rates increased the retention time which in turn increased the chances of the material to be broken, and thus reduce the particle size.
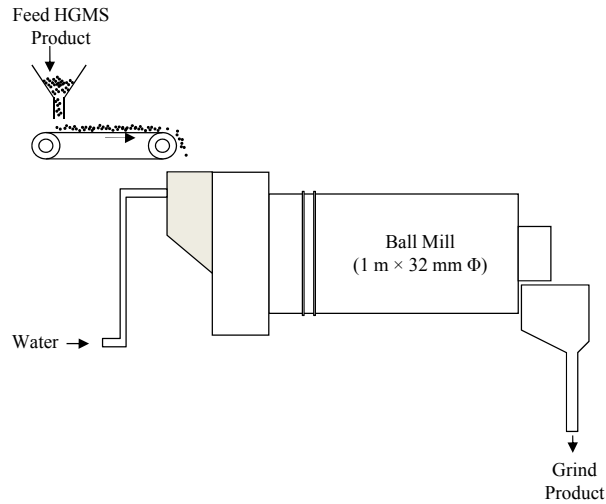
Figure 16. Schematic diagram of the ball mill circuit set up.

Figure 17 shows the cumulative passing of material as a function of particle size fraction for different grind variants produced as a result of grinding in the ball mill. Each grind variant represents a certain cumulative retention time in ball mill. Suspension stability was qualitatively assessed during the grinding trials. A residence time of 52 minutes was required to achieve good medium stability, which provided a mean particle size of about 22µm and a d_{90} of about 48µm.
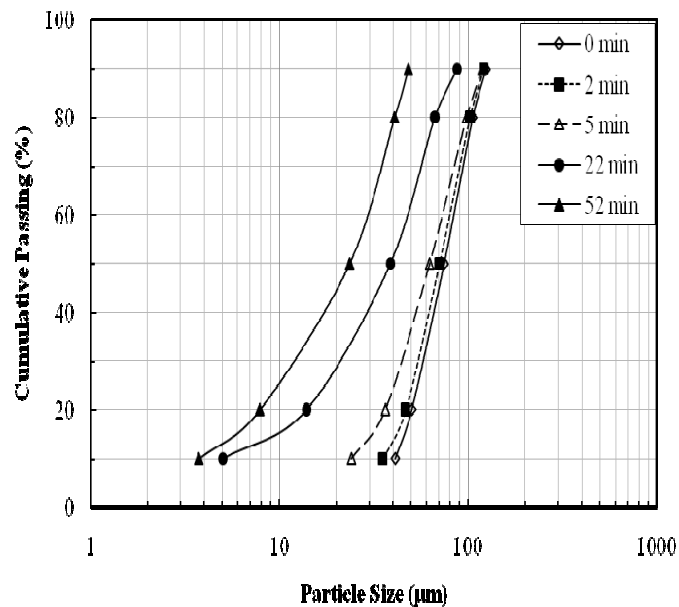

Figure 17. Change in particle size distribution with increased retention time in ball mill.

The medium formed from grinding the bottom ash material using a 52 minute retention time was observed to be more stable with relative density differences being within the industrial acceptable levels of around 0.4 density units and less (Figure 18). In fact, the magnetic bottom ash medium was found to be more stable than the medium formed using conventional Grade B magnetite. With an increase in relative medium density, the suspension provided for improved stability due to the elevated impacts of hindered settling and medium viscosity.
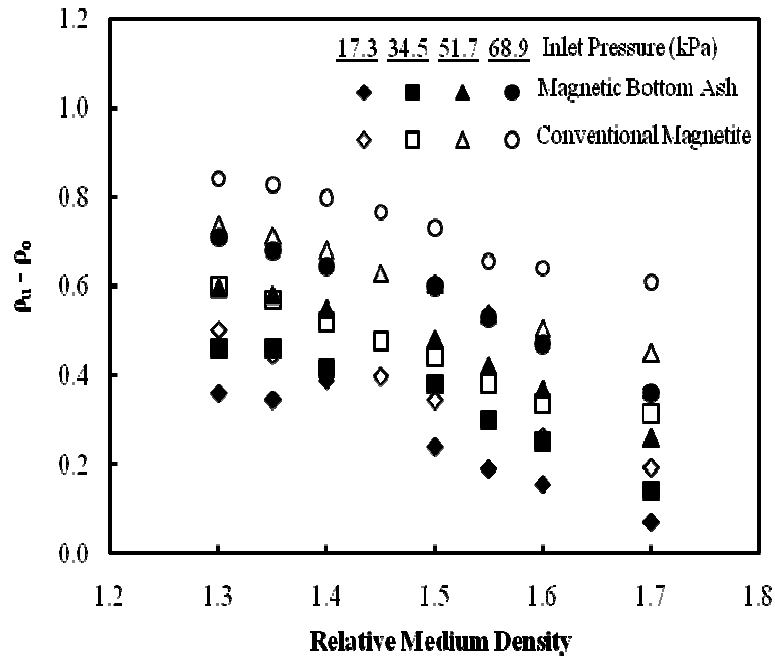

Figure 18. Comparison of medium stability achieved by ground bottom ash and grade 'B' magnetite.

DM Cyclone Performance

Dense medium cyclone tests were conducted to assess the separation efficiency achievable when using the magnetic bottom ash. Washability analyses were performed on samples collected from the clean coal, reject and feed process streams. The data was used to develop the partition curves shown in Figure 19 over a range in medium density values from 1.4RD to 1.7RD.

A sign of medium stability is a low density offset, which is the difference between the actual separation density (ρ_{50}) and the medium density. At medium density values of 1.4RD and 1.5RD, the density offset was relatively high with values around 0.08 density units. At 1.6RD, the offset drops to 0.04 density units indicating medium stabilization.

Separation efficiency is measured by the slope of the partition curve which is typically quantified by the probable error value (i.e., $Ep = [\rho_{25}-\rho_{75}]/2$). Bypass of low-density particles to the reject stream and vice versa are also a sign of inefficiency. A parameter that combines the efficiency associated with the probable error and bypass is the organic efficiency. Organic efficiency is the ratio of the actual energy recovery to the theoretical energy recovery at a given product quality or product ash content. A summary of the separation performances represented in Figure 19 is shown in Table 6.
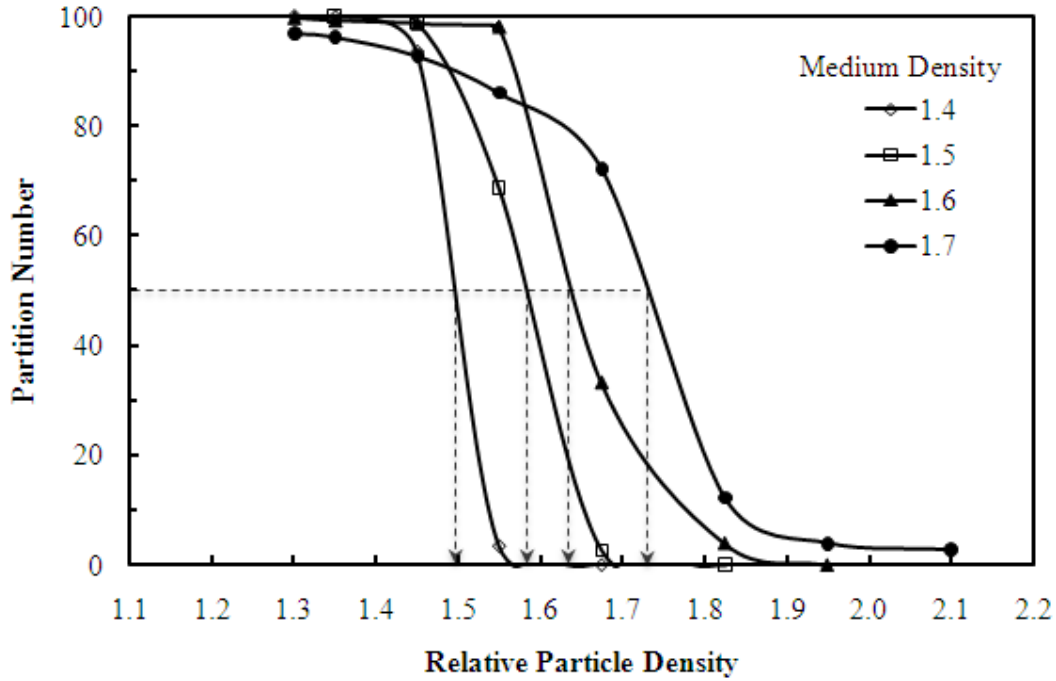

Figure 19. Partition curves generated over a range of medium density values using magnetic bottom ash.

Variable	Relative Medium Density			
	1.4	1.5	1.6	1.7
Feed Ash (%)	40.84	40.30	33.82	32.58
Product Ash (%)	6.11	8.82	11.7	15.43
Tailings Ash (%)	56.44	58.28	57.82	56.29
Yield (%)	31.00	36.36	52.04	58.03
Recovery (%)	49.19	55.53	69.43	72.79
Org. Efficiency (%)	96.81	98.92	95.49	89.94
ρ_{50}	1.495	1.583	1.640	1.733
E_p	0.023	0.044	0.051	0.063
$\rho_{50} - \rho_{medium}$	0.095	0.083	0.040	0.033

Table 6. Summary of separation performances achieved using the magnetic bottom ash at an inlet pressure of 34.5 kPa.

The separation efficiencies measured for the medium densities of 1.4RD and 1.5RD are excellent with organic efficiency values around 97% and probable error values of 0.04 and less. As the case with conventional magnetite, the probable error increases with an increase in medium density which represents a decline in efficiency due to medium viscosity impacts. The probable error values are comparable to those achieved when using conventional magnetite.

A trend that is atypical is the decline in organic efficiency with an elevation in medium density. In most cases, the amount of near gravity material in the feed coal decreases within the middle density fractions. As a result, organic efficiency generally improves with an increase in medium despite the declining efficiency caused by medium viscosity. For the coal in this study, a peak in middlings content occurs at a density around 1.75 which causes the inefficiencies quantified by the probable error values to by magnified in the determination of organic efficiency.

An inlet pressure of 34.5 kPa has been noted to provide a centrifugal force higher than that applied by an industrial 700 mm diameter DMC by about 2 or 3 g's. Therefore, the comparison of separation performance with industry data is best provided with results at this pressure. However, stability curves from Figure 18 indicated that the ground magnetic bottom ash displayed good medium characteristics at a higher inlet pressure of 51.7 kPa and at medium density values greater than 1.5 RD. As a result, the separation performance at this pressure was evaluated and the partition curves of separation obtained are plotted in Figure 20.

A medium density of 1.5 RD provided the best separation performance as can be observed from steep slope of partition curves. However, the density offset was very high indicating a relatively unstable medium suspension at 1.5 RD as compared to those realized at densities of 1.6 and 1.7 RD. Davis and Napier-Munn (1987), when trying to stabilize the magnetite medium in DMC by increasing the fine clay contamination, observed similar phenomenon to occur and concluded that the cut-point shift decreased as the medium stability increased. Achieving a better separation efficiency at a medium density of 1.5RD despite inferior stability characteristics can be attributed to the combined effect of an elevated centrifugal force and improved medium rheology.
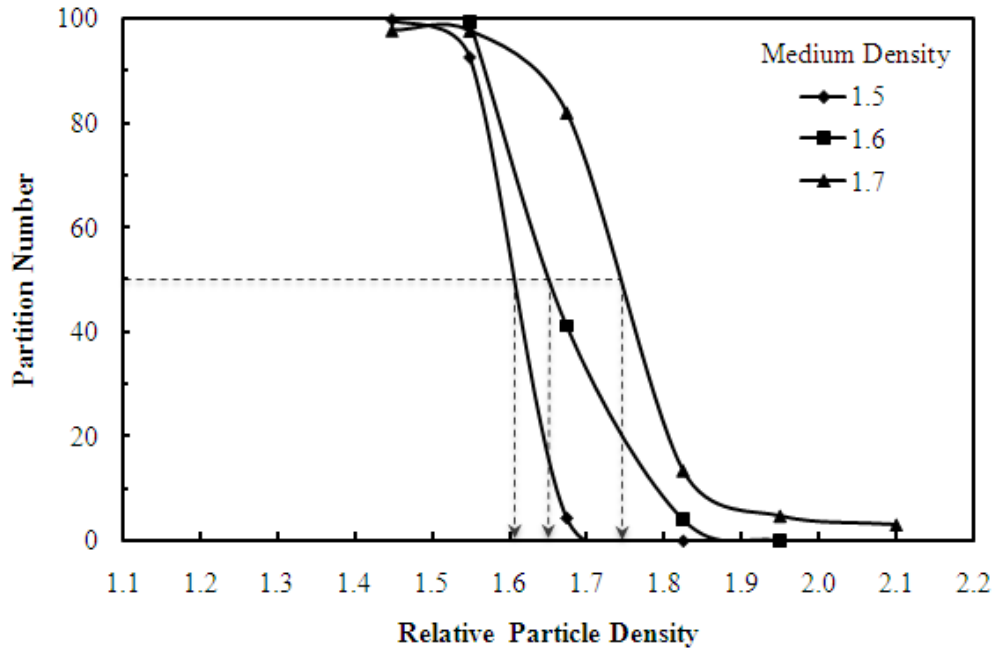
Figure 20. Partition curves generated from separation performances achieved over a range of medium density values using an inlet pressure of 51.7 kPa (7.5 psi).

In a dense medium cyclone, centrifugal force impacts the particle velocity thereby affecting separation performance (Clarkson et al., 1998). Near-gravity particles tend to move slowly due to small density difference between the particle and the medium. An increase in centrifugal force enhances the force on high density particles to overcome yield stress, in turn enhancing velocity of these particles which leads to a sharper separation. However, with increased relative medium density the effects medium rheology dominates over centrifugal force. Elevated medium viscosity and the high yield stress contribute to low separation efficiency at medium density of 1.6 and 1.7 RD. The separation performances achieved by the ground bottom ash using an inlet pressure of 51.7 kPa are summarized in Table 7.

At a relative medium density of 1.5 RD, bottom ash based medium formed exhibited very good cleaning characteristics with a high organic efficiency and E_p value of 0.03. Organic efficiency dropped at higher medium densities as a result of bypass of material occurring in the process. The organic efficiency observed was higher at this pressure when compared with performance of medium at 34.5 kPa.

Variable	Relative Medium Density		
	1.5	1.6	1.7
Feed Ash (%)	33.84	29.06	29.40
Product Ash (%)	8.52	11.17	15.66
Tailings Ash (%)	58.46	56.34	58.19
Yield (%)	49.3	60.4	67.7
Recovery (%)	68.2	75.6	80.9
Org. Efficiency (%)	99.5	97.7	95.7
ρ_{50}	1.608	1.653	1.745
E_p	0.030	0.063	0.051
ρ_{50} - ρ_{medium}	0.108	0.053	0.045

Table 7. Summary of separation performances achieved using the magnetic bottom ash at an inlet pressure of 51.7 kPa.

Magnetic Bottom Ash Recovery

The magnetic properties of the ball mill grind product were measured using a Davis Magnetic Tube. The Davis Magnetic Tube apparatus consists of an extremely powerful electromagnet, which has the capability of producing magnetic field intensity of up to 4000 gauss, a glass separation tube and a motor driven agitation mechanism. The tube is positioned between the poles of the magnet at an angle of approximately 45 degrees. The set up is driven by a small motor which drives the agitating mechanism that supports the water filled glass tube. The tube moves forward and backward while it rotates simultaneously. The set up allowed variable speeds of oscillation from 1 to 90 cycles per minute and a tube rotation of 120° with a stroke length of 51 mm (2 inches). Figure 21 shows a typical Eriez's Davis tube tester Model EDT.
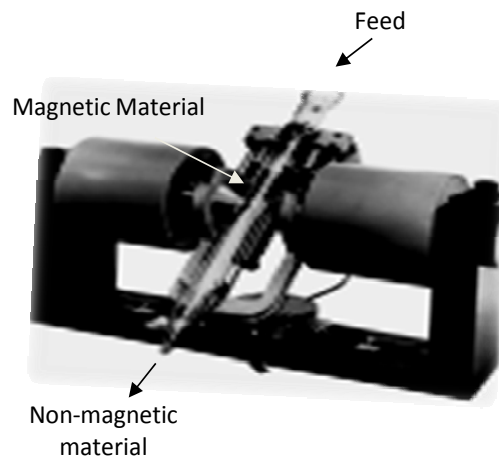

Figure 21. Eriez Davis Tube Tester Model EDT.

A representative sample of each ball mill grind product was introduced into the Davis tube with the oscillation rate set to 50 cycles per minute. The magnetic particles were collected in the zone of intense magnetism and a vigorous washing action by agitation was applied to these particles. All the non-magnetic particles were flushed from the tube. The magnetic field was de-activated and the clean magnetic concentrate was collected. To ensure better determination of the magnetic content, a retention time of 45 minutes was allowed for each test. The samples were dried and weighed and the amount of magnetics was calculated. The collected magnetic material was again introduced into the Davis tube to test the amount of magnetic material collected as a function of magnetic intensity.

In addition to DMC separation performance, magnetic recovery is another important issue in development of recovered magnetic material as an alternative to magnetite. Magnetic content of the initial recovered material was 74%. After grinding the bottom ash material, the magnetic components were selectively liberated. This action reduced the amount of magnetic particles in the original feed to 54%. However, the magnetic strength needed to recover the material was significantly reduced as shown in Figure 22. The magnetic strength needed is about 1000 gauss to recover 98% of the material. The typical magnetic field strength provided by the low-intensity wet drum commonly employed in the coal industry is 750 gauss.
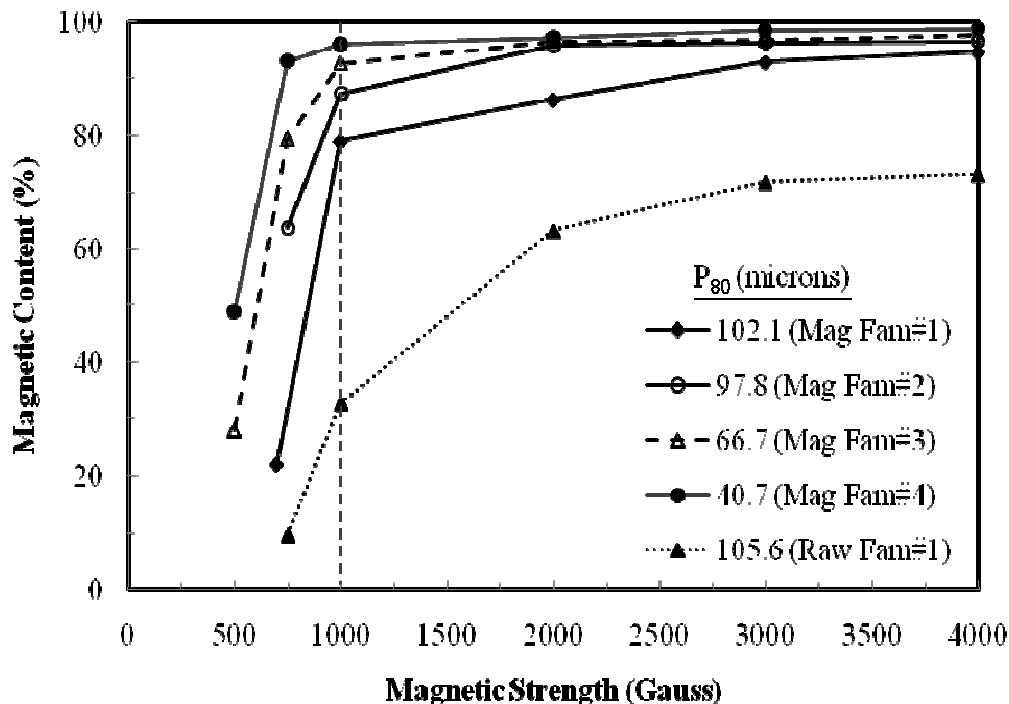

Figure 22. Field Strength Required to Recover Magnetic Material.

SUMMARY AND CONCLUSIONS

A study had been performed to assess the feasibility of using magnetic material collected from the bottom ash material of a pulverized coal boiler as a substitute for magnetite in dense medium separations used for cleaning coal. The findings can be summarized as follows:

1. About 6% of a bottom ash material generated at a utility using high sulfur coal was found to be magnetic and recoverable using a combination of spiral concentrators and magnetic separators.

2. The magnetic bottom ash particles were spherical in shape and coarser than conventional magnetite. The medium generated using the original magnetic particles was unstable.

3. Grinding reduced sphericity and size of the magnetic particles which enabled the generation of a relatively stable medium within a dense medium cyclone.

4. The magnetic components of the bottom ash were selectively liberated during grinding which reduced the quantity of the recoverable magnetic material. However, the magnetic field strength needed to recover 98% of the magnetic bottom ash material was reduced to around 1000 gauss, which is near the level of the low-intensity drum current used in the coal industry.

5. The separations achieved using the magnetic bottom ash particles are comparable to those achieved through the use of conventional magnetite. Probable error values ranged from 0.02 at a medium density of 1.4RD to 0.06 at 1.7RD. For the bottom ash material used in this study, the upper medium density limit appears to be around 1.6RD. Above this value, medium viscosity appears to have a significant impact.